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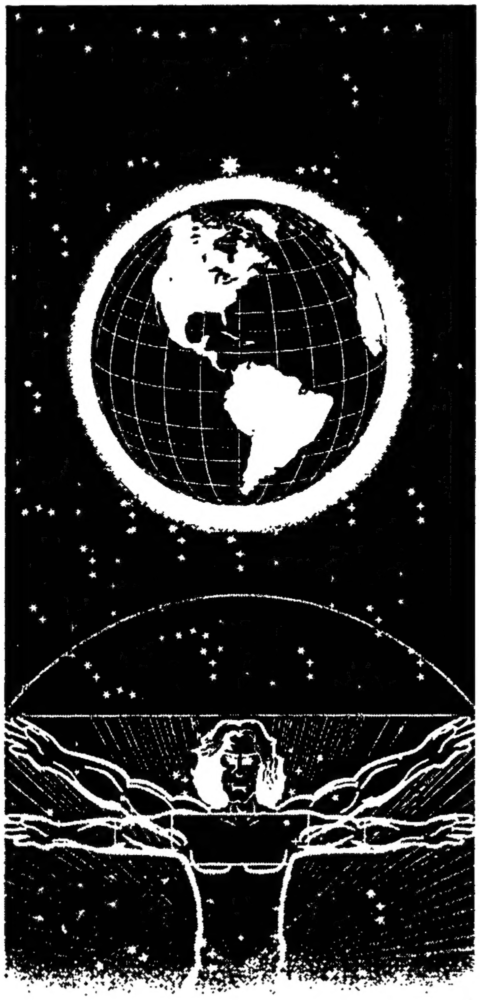

UNITED STATES AIR FORCE RESEARCH LABORATORY

A STUDY OF THE EFFECTS OF MULTIPLE-PULSED LASER EXPOSURE ON INCREMENT THRESHOLDS

Peter Smith
William Kosnik
Leon McLin
Brenda Novar

Northrop Grumman Information Technology
4241 Woodcock Drive, Ste B-100
San Antonio, TX 78228

HUMAN EFFECTIVENESS DIRECTORATE
DIRECTED ENERGY BIOEFFECTS DIVISION
OPTICAL RADIATION BRANCH
2650 LOUIS BAUER DRIVE
Brooks City-Base TX 78235-5214

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14. ABSTRACT
Little is known about the effects of brief, repetitive laser pulses in the microsecond and sub-microsecond range on visual adaptation. Although it is generally acknowledged that, for pulsed light exposures from 1 to 150 ms, the total energy of a flash (intensity x duration) determines its brightness or adaptation potential, there are little data supporting this reciprocal relationship in human subjects. The purpose of this study was to compare the increment threshold for a spot target superimposed on an extended source image of a pulsed laser source, and to evaluate whether reciprocity holds. Eight subjects completed a method-of-adjustment determination of increment threshold for a 023 white test spot viewed superimposed on an extended source image (o.61) of a green (532 nm) laser beam. The laser pulse durations were 10 us, 100us, 1ms and 10 ms at 3 Hz and 10Hz. In addition, the effect of continuous wave (CW) exposure was determined. The time-average laser exposure was held constant across all the laser conditions. For the 3 Hz pulse condition, the threshold luminance was much lower than for the CW condition and there was no effect of pulse width, i.e. reciprocity was observed. However, thresholds for the 1 ms and 10 ms pulses at 10 Hz were higher than for the DW case, and this reciprocity failure was interrupted as a brightness enhancement effect. More pulse durations and pulse rates must be studied before this failure can be more fully understood.

15. SUBJECT TERMS
Laser, Visual Psychophysics, Visual Perception, Flicker, Brightness Enhancement, Light Adaptation, Glare, Flashblindness

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1 INTRODUCTION

Lasers pose an ever-increasing threat in the aerial environment, because of their increasing portability and the large number of different laser types and wavelengths. The proliferation of lasers operating in the visible spectrum (400-760 nm) is a potentially severe problem for pilots, since exposure to even low levels of visible laser radiation can cause temporary visual deficits that can compromise safe operation of the aircraft and decrease the probability of mission success. The effects of visible laser radiation can range from transient glare (the visual loss while the laser is on) and flashblindness (the temporary visual loss following the termination of the laser), to permanent eye damage.

There are laser bioeffects models for predicting exposure levels for permanent damage, but they do not model the transient functional decrements produced by intense light. Even dedicated models of transient effects do not adequately predict flashblindness recovery within the first second after the exposure, nor do they predict the effects of multiple exposures (McLin, Previc, Smith, Kosnik, & Barsalou, 2001). These models also assume reciprocity between the duration and intensity of the flash, but this is a valid assumption only up to ~150 ms (the latency of the ocular aversion reflex) and may not be valid at flash durations less than a millisecond (Kosnik, 2002; Kosnik & Smith, 2003). Moreover, no laser effects model has been developed to predict visibility during exposure to a train of multiple pulses. The importance of the above issue lies in the fact that existing laser systems are capable of delivering a long train of short-duration (<1 μs) flashes to pilots.

Most data obtained from humans suggest that for exposures ranging from 1-150 ms the total energy of a flash (intensity × duration) determines its brightness or adaptation potential (Brindley, 1952; Crawford, 1946; McLin et al., 2001; Watson, 1986). A number of studies have tried to determine the lower time limit for reciprocity and have found it to be influenced by many factors including light adaptation level (Barlow & Sparrock, 1964; Crawford, 1937; Stewart, 1972), the spatial extent of the light (Barlow, 1958; Hood & Finkelstein, 1986; Karn, 1936), and its wavelength (Sperling & Jolliffe, 1965). The shortest period of time for which reciprocity holds was investigated specifically by Brindley (1952). He investigated equal energy supra-threshold exposures between 8.9 ms and 0.4 μs and found that reciprocity held all the way down to the shortest duration. However, Brindley was restricted in the total energy he could deliver at the shortest durations by the limited intensity of conventional incandescent light sources and the luminous energy of his flashes in this range was extremely low - less than 0.3 troland-seconds (td-s).

Three electrophysiological studies using non-human primates also reported a reciprocity between the effects of Q-switched pulses in the nanosecond range and continuous-wave (CW) exposures, when all laser energy was delivered within 100 ms. Two of these studies used visual evoked potentials (VEPs) to measure flashblindness recovery for short- and long-duration pulses of similar wavelengths – 12 ns at 532 nm versus CW at 515 nm (Previc, Allen, & Blankenstein, 1985) and 20 ns at 694 nm versus CW at 676 nm (Schmeisser, 1987). The third study, which compared responses to 20 ns, 532 nm pulses versus a 515 nm CW exposure (Glickman, 1987), observed a monotonic relationship between laser energy and the firing rate of retinal ganglion

cells. Yet a fourth study showed similar laser-induced adaptation in the VEP for equivalent combined photopic energies in pulse-trains delivered within 200 ms, regardless of the number of pulses included in each train (Previc, 1987).

Any reciprocity between short- and long-pulses presumably requires a neural adaptation process as well as a photopigment bleaching process, given that short pulses have been shown to bleach no more than 50% of retinal pigment (Rushton, 1964). However, virtually no studies exist regarding the behavior of this putative neural mechanism in the sub-millisecond range.

Perhaps more importantly, earlier studies comparing short- and long-duration exposures and different types of pulse-trains have used post-flash recovery as the dependent measure. None has tried to investigate the behavior of the visual system during the exposure train-- i.e. the inter-pulse visibility. The evidence is mixed as to whether a CW or pulsed-laser glare source of equivalent time-averaged luminous energy is more effective in disrupting visual function. For high-resolution target-recognition tasks, pulse-trains of non-laser light with frequencies less than 10 Hz appear to be less effective than CW exposures of the same average energy (Smith, 1996), presumably because some recovery from flashblindness occurs in the first few hundred milliseconds following each pulse. However, pulsed lasers may be more effective than CW ones of the same average power in disrupting more complex tasks, such as aircraft attitude control and others that require a great deal of motion processing (Beer & Gallaway, 1999). This is because strobing destroys the continuous velocity information required for many visuomotor tasks (Green, 1981).

It is difficult to measure flashblindness in the first few hundred milliseconds following a flash, because of the time required for the subject to make the visual threshold judgment. Therefore, an experiment using both a CW and pulsed laser train can be used to not only compare the effects of multiple-pulse versus CW exposures, but it can also provide an estimate of flashblindness recovery during the first few hundred milliseconds after each pulse. For example, Smith (1996) showed that an non laser light pulse train with an integrated retinal illuminance of 3.0 log td-s disrupted a letter-identification task at 10 Hz but not at 3 Hz, implying that recovery from flashblindness was sufficient to perform the task by 300 ms post-flash but not by 100 ms post-flash. If, on the other hand, the integrated luminous energy of the flash was increased to 4.5 log td-s, even a 1 Hz pulse train could disrupt the visual task. This implies that sufficient recovery from flashblindness had not occurred in the first second following the higher-energy flash.

The present study investigated the effects of trains of short-duration laser pulses on visual function using an increment-threshold task. By observing the effects of exposure to a 10 s continuous wave pulse, and 3 Hz and 10 Hz pulse trains, with pulse durations from 10 μs to 10 ms, all with the same time-average intensity, we were able to test the intensity × duration relationship. The increment-threshold task that was used in this study, particularly the CW exposure condition, has general predictive validity because it can be used to provide a direct estimate of the equivalent background luminance produced by the afterimage of the pulse.

2 METHODS

2.1 Subjects

A total of eight subjects participated in the study. Six were males and two were females, with a mean age of 38.5 years. The subjects were all naïve as to the presentation order of the conditions. All subjects had a visual acuity equal to at least 20/25 in each eye (corrected where necessary), although they viewed the stimuli in this experiment using one eye only. All subjects received a laser eye examination within 45 days prior to their participation in the experiment, and were offered an optional post-experimental laser eye exam, to be carried out within 45 days of their participation. Each laser eye examination included the following tests: visual acuity, slit-lamp, color vision, stereopsis, Amsler Grid, and dilated fundus evaluation and photography.

2.2 Apparatus and methods

A schematic diagram of the optical system used in the experiment is shown in Figure 1. Subjects were seated in an adjustable chair behind an occluding screen in a darkened room, with their head supported by a chin-rest. They used their preferred eye to view a 0.23° test stimulus superimposed on a 0.61° adapting laser field (see Inset: Figure 1). The other eye was covered with an eye patch.

The test stimulus was generated by a quartz tungsten halogen (QTH) lamp connected to a radiometric power supply (300W, Oriel Corporation, Model #68831) projected onto a diffusing glass screen, which was viewed via an artificial pupil (3 mm diameter) located just in front of the eye, an electronic shutter (#1) set into the occluding screen, and a mirror, beam splitter, second electronic shutter (#2) and variable neutral density filter wheel. The size of the artificial pupil was chosen to be less than the natural diameter of the pupil for all experimental conditions, and served to eliminate any effects that may be due to variations in pupil size. The variable neutral density filter wheel was used to control the luminance of the test stimulus.

The visual task was a luminance increment-threshold task for detection of the test stimulus against the adapting field, the threshold being determined by the method-of-adjustment. Prior to the commencement of each trial the starting position of the variable neutral density filter was set randomly to maximum transmission (0.1ND) or maximum absorption (3ND). This determined whether the test trial was to be "descending" or "ascending", respectively. Four red light-emitting diodes (LEDs) mounted around the test-stimulus aperture at the oblique meridians and co-linear with the laser beam were provided to allow the subjects to align themselves with the optical path.

At the start of each trial shutters #2 and #3 were closed, shutter #1 was opened and the LEDs were illuminated. The subjects aligned themselves and when they were ready they initiated the trial by pushing a button on the response panel. When the trial was initiated the LEDs were turned off and, after a 1 s delay, shutter #3 opened to turn on the laser beam. After a brief adaptation period (0.5 s) the test stimulus was turned on by opening shutter #2. The subject then used a toggle switch mounted on the response panel to control the position of the filter wheel, and hence the luminance of the test stimulus. The filter wheel moved at $90°s^{-1}$ (equivalent to $1ND.s^{-1}$)

during the subject's first switch movement. During each subsequent switch movement the rate was reduced by $30°s^{-1}$, $15°s^{-1}$, $7.5°s^{-1}$ and so on for each successive movement until the subject established his or her visual threshold. When the subject was satisfied that the stimulus was at threshold, i.e. just visible, they pressed the push button a second time, which closed all the shutters and ended the trial. The maximum time allowed for each of the trials was 10 s, starting from the time of onset of laser exposure. If the subject had not established a threshold within this time the trial timed-out, and all the shutters were closed automatically.

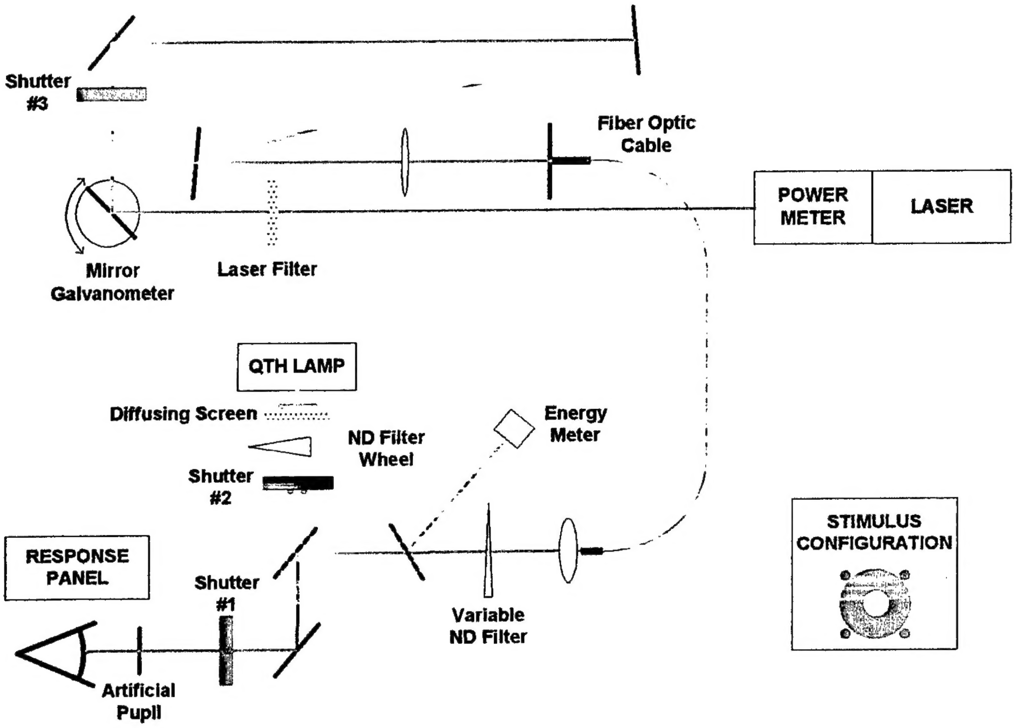

Figure 1. The optical system used to present the laser beam and test stimulus.
Inset: Stimulus configuration.

2.3 Laser Exposures

The laser exposures were generated by a neodymium laser (Coherent Verdi Nd:VAO_4), whose output was frequency doubled and centered at 532 nm. The laser beam was launched into a fiber-optic cable using a moving mirror mounted on an open-loop mirror galvanometer (GSI Lumonics G330 Series). The galvanometer movement was driven by a computer generated analog waveform, and using the moving mirror to scan the laser beam across the entry aperture of the fiber-optic generated the pulsed laser exposures. At the other end of the fiber optic cable the tip of the emerging beam was magnified to produce a 0.61° spot (at the subject's eye position) that was reflected off a beam-splitter and mirror and into the subject's eye. The final spatial profile of the laser approximated a Gaussian distribution - a typical spatial distribution for the beam is shown in Figure 2.

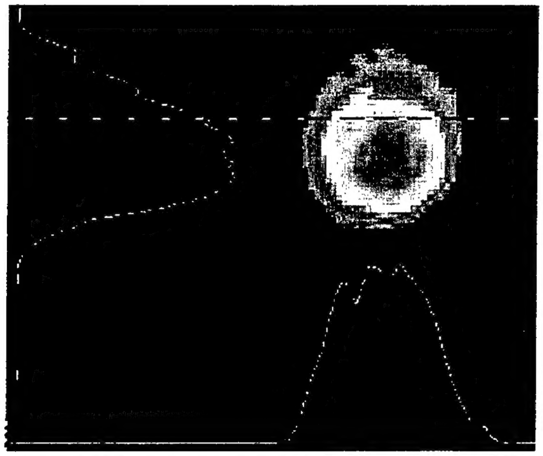

Figure 2. Typical spatial beam profile

Nine different laser exposure conditions were presented to the subject. These were either continuous wave (CW), or pulse trains consisting of 10 μs, 100 μs, 1 ms or 10 ms (FWHM[b]) at 3 Hz or 10 Hz. The waveforms required to control the mirror, and thereby generate pulses of the required duration and pulse repetition frequency, were carefully designed and tested prior to the commencement of the study. The temporal profiles of the pulses, each of which conformed to an approximately Gaussian profile are shown in Figure 3.

Before each exposure condition, the duration and pulse repetition frequency was checked using a photodiode detector whose output was displayed on an oscilloscope. The pulse energy (or power in the case of the CW condition) of the laser exposure was measured at the subjects' eye position by means of a silicon detector (Newport model #818-SL). A second detector (CW conditions: Newport 818-SL, pulsed conditions: Laser Probe RM-6600) at the fiber optic exit was cross calibrated with the reading at the eye position. The cross-calibrated detector was used to measure the laser exposure during each trial, and the control computer recorded these values.

For the continuous wave (CW) condition the power of the beam in the subject's pupil plane was 19.8 $nW \cdot cm^{-2}$, leading to a total intraocular exposure (through the 3 mm artificial pupil) of 1.4 nW. For the pulsed exposure conditions, the energy in each pulse was set such that the average power was the same as for the CW condition. Thus for 3Hz and 10Hz conditions the energy required in each pulse was 6.60 and 1.98 $nJ \cdot cm^{-2}$ respectively. To change between the 10 μs and 10 ms exposure conditions, the peak power of the CW laser needed to be adjusted over a range of three log units. This was achieved by a combination of placing fixed absorption filters before the mirror galvanometer, and a filter wedge placed at the exit aperture of the fiber optic.

The laser exposure parameters for each condition are given in Table 1. In photometric quantities, the luminance of the CW beam was 1346.0 $cd \cdot m^{-2}$, and provided a retinal illumination of 3.98 log

[b] FWHM = Full-Width Half-Maximum

trolands through the 3 mm pupil. The integrated retinal illuminance of each pulse for the 10 Hz and 3 Hz pulses was 2.98 and 3.50 log troland-seconds respectively, with the average retinal illumination of the pulse-trains being equal to the continuous exposure.

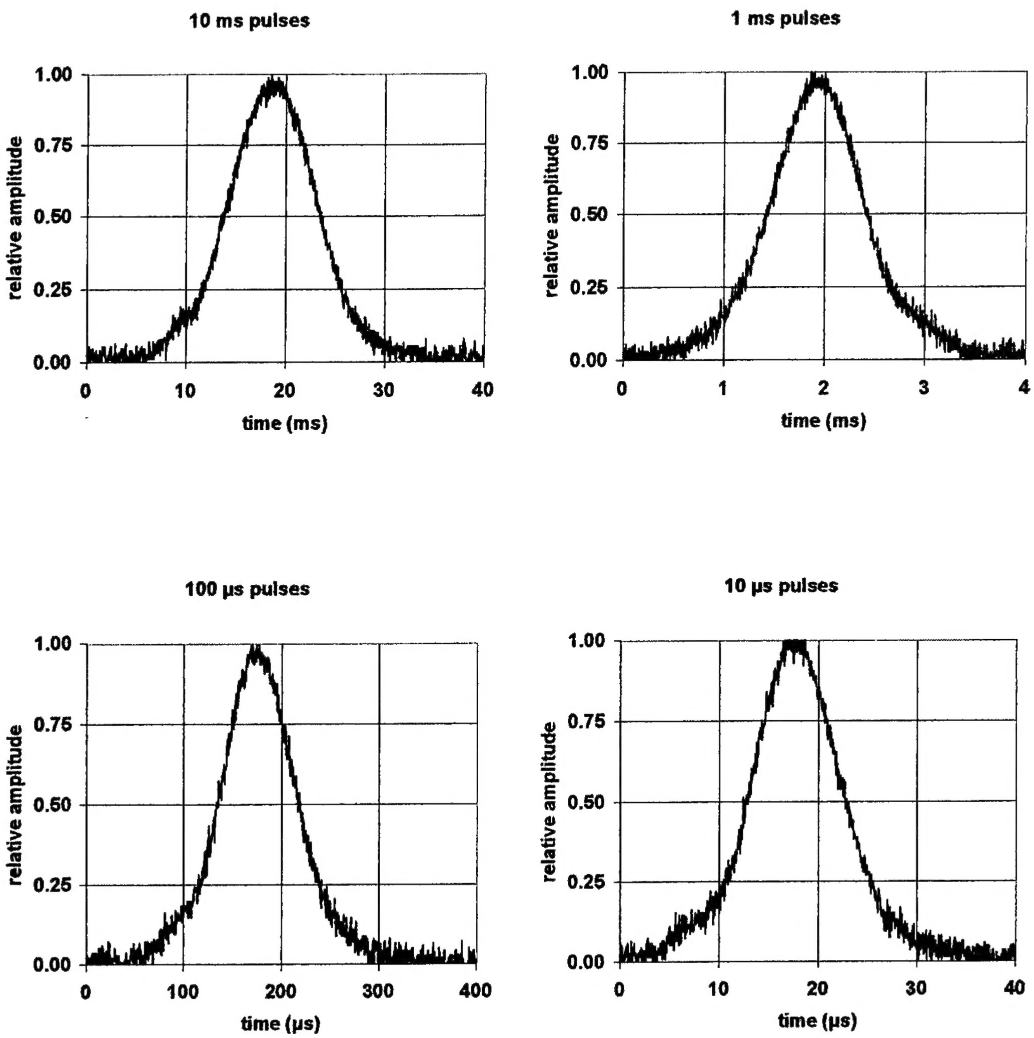

Figure 3. Temporal profiles of the laser pulses

Table 1. Laser exposure parameters

Frequency	Pulsewidth	Radiant Exposure per pulse ($J \cdot cm^{-2}$)	Peak Irradiance per pulse ($W \cdot cm^{-2}$)	Time-Average Power ($W \cdot cm^{-2}$)	Time-Average Luminance[a] ($cd \cdot m^{-2}$)
CW	n/a	n/a	1.98×10^{-8}	1.98×10^{-8}	1346.0
10 Hz	10 μs	1.98×10^{-9}	1.98×10^{-4}	1.98×10^{-8}	1346.0
	100 μs	1.98×10^{-9}	1.98×10^{-5}	1.98×10^{-8}	1346.0
	1 ms	1.98×10^{-9}	1.98×10^{-6}	1.98×10^{-8}	1346.0
	10 ms	1.98×10^{-9}	1.98×10^{-7}	1.98×10^{-8}	1346.0
3 Hz	10 μs	6.60×10^{-9}	6.60×10^{-4}	1.98×10^{-8}	1346.0
	100 μs	6.60×10^{-9}	6.60×10^{-5}	1.98×10^{-8}	1346.0
	1 ms	6.60×10^{-9}	6.60×10^{-6}	1.98×10^{-8}	1346.0
	10 ms	6.60×10^{-9}	6.60×10^{-7}	1.98×10^{-8}	1346.0

[a]Calculated as: average power ($W \cdot cm^{-2}$) × luminous efficacy (= 0.883 @ 532 nm) × 683 (lumens per watt) × 10^4 (conversion from $\cdot cm^{-2}$ to $\cdot m^{-2}$) ÷ 8.9×10^{-5} (solid angle subtended by the 0.61° source)

An elaborate safety system, for the most part controlled by the computer, ensured that the pulse-width, frequency, and power of the laser were all within tolerance (±20% of specified values) before each trial commenced. A dedicated circuit with its own fast photodiode (Thor Labs 210) monitored the energy of the pulse, so that either an increase in pulse-duration or peak-power would terminate the trial within 2 ms by closing a shutter (Uniblitz 225L) attached to the screen located in front of the subject.

2.4 Overall Design

This experiment was conducted using a completely within-subjects (repeated-measures) design. Subjects were exposed to nine different laser conditions (4 pulse widths × 2 pulse repetition frequencies + 2 CW). There was one replication of each condition and ten increment thresholds determinations (trials) were made for each exposure condition. The order of the conditions and their replications were randomized and balanced across subjects. To include one replication of each condition, six sessions lasting approximately one hour each were required, with four conditions being tested in each session. Subjects received two 45-min training sessions on the increment-threshold task prior to the first laser-exposure session.

3 RESULTS

A preliminary analysis of the experimental results reveled that one subject had clearly not understood the requirements of the psychophysical task, and so his results were excluded from the analysis. In addition, two of the subjects appeared to exhibit "hypersensitivity" to the 10Hz, 1 ms and 10 Hz, 10 ms conditions, in that their increment thresholds were much higher compared to the other subjects, and compared to their own thresholds at other pulse widths. The results from these subjects were also excluded from the statistical analysis.

For the remaining five subjects, the average increment threshold luminance for detecting the presence of the test stimulus against the laser background in the CW condition was 124.8 cd.m^{-2}. Since the photopic luminance of the laser was approximately 1346.0 cd·m^{-2}, the luminance contrast threshold for the CW condition was 9.27%[c].

The thresholds in each laser exposure condition were averaged across trials and subjected to a repeated-measures analysis-of-variance with one between-subjects factor (subjects) and two within-subjects factors (laser pulse width and pulse repetition frequency). A log transformation was applied to the data to equalize variances across the conditions. This analysis revealed a main effect of frequency {$F(1,4) = 499.1$, $p < 0.0001$}, and frequency × pulse width interaction {$F(3,12) = 16.68$, $p < 0.0001$}. For the 3 Hz pulse condition, the threshold luminance was much lower than for the CW condition ($p<0.001$) and there was no effect of pulse width on the threshold. Tukey HSD post-hoc tests revealed that luminance thresholds for the 1 ms, 10 Hz and the 10 ms, 10 Hz condition were higher than for the CW, 3 Hz, and 10 Hz, 10 µs, and 10 Hz, 100 µs conditions (all $p<0.05$), but the 1ms and 10 ms, 10 Hz conditions were not different from each other. Furthermore, the 10 us and 100 us 10 Hz conditions were not significantly different from the CW conditions. The luminance thresholds for each condition are plotted in Figure 4, and shown in Table 2.

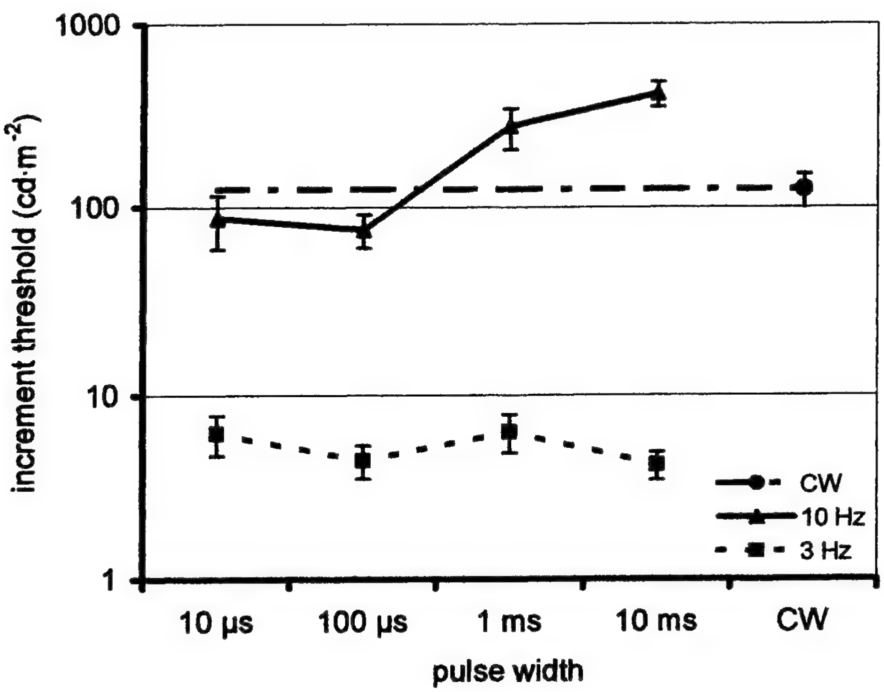

Figure 4. Effect of laser condition on luminance increment thresholds (±SEM).

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[c] contrast was calculated as the superimposed test stimulus (i.e. target) luminance divided by the time-average laser (i.e. background) luminance

Table 2 also includes the equivalent background luminance levels for the pulsed laser conditions. These are calculated relative to the background luminance and the increment threshold luminance for the CW condition, and provide an indication of the effectiveness of the flickering field as an adapting background.

Frequency	Pulsewidth	Time-Averaged Background Luminance ($cd \cdot m^{-2}$)	Increment Threshold Luminance ($cd \cdot m^{-2}$)	Equivalent Background Luminance ($cd \cdot m^{-2}$)
CW	n/a	1346.0	124.8	----
10 Hz	10 μs	1346.0	87.3	941.6
	100 μs	1346.0	75.6	815.1
	1 ms	1346.0	273.6	2950.1
	10 ms	1346.0	414.1	4464.4
3 Hz	10 μs	1346.0	6.3	67.7
	100 μs	1346.0	4.5	48.1
	1 ms	1346.0	6.4	68.9
	10 ms	1346.0	4.2	45.5

Table 2. Increment thresholds and equivalent background luminance levels.

4 DISCUSSION

The key findings of this study are notable in several important respects. Firstly, compared to a CW field, increment thresholds were lower when viewed against a 3 Hz adapting field, and these thresholds were unaffected by the pulse duration between 10 μs and 10ms. Secondly, when the pulse repetition frequency of the adapting field was increased from 3 Hz to 10 Hz, increment thresholds were higher than in the 3 Hz condition. Thirdly, compared to a CW field, for an adapting field at 10 Hz, increment thresholds were lower for 10 μs or 100 μs pulses, and higher for 1 ms or 10 ms pulses. Finally, at 10 Hz there was no difference in increment thresholds between 10 μs and 100 μs pulses, but increment thresholds were higher for 1ms pulses, and further elevated for 10 ms pulses. Note that for all exposure conditions the time-average power was held constant.

In general, the results are consistent with the results of Smith (1996), who, using chopped conventional light sources, and similar pulse rates (CW, 3 & 10 Hz), pulse widths (down to 6 ms), and paradigm (method-of-adjustment, albeit to vary the luminance of the adapting field and not the luminance of the stimulus), showed that, compared to a CW source, the luminance of a flickering adapting field needed to be increased to obscure a target stimulus. The magnitude of the increase was about 40-fold for 3 Hz and 4-fold for 10 Hz pulses. Similarly, in the present study, increment thresholds were reduced (compared to a CW adapting field) for the 3 Hz pulse trains, although the magnitude of the reduction was less (~20-fold reduction). These results indicate that there is some visual recovery in between the pulses, and that to maintain increment thresholds at the same level as the CW exposure, the luminance of the individual pulses would

need to be increased. The same was true for the 10 Hz pulse trains if the pulse width was less than 1 ms (~1.5-fold reduction).

A surprising result is that while a reciprocal relationship between pulse intensity and duration held for 3 Hz pulses, this relationship did not hold at 10 Hz, where pulse durations of 1 ms and 10 ms produced higher increment thresholds than 10 μs and 100 μs pulses. Indeed, the increment thresholds for the longer pulses were higher than for a CW exposure. This finding should first be considered in the context of Bloch's law of reciprocity, which states that the detectability of a near-threshold flash of light remains constant as long as the product of stimulus intensity and duration is held constant. Indeed, we expected reciprocity to hold for pulse durations into the nanosecond domain on the basis of previous monkey electrophysiological studies (Glickman, 1987; Previc, 1987; Previc et al., 1985; Schmeisser, 1987), although those findings provided mainly qualitative evidence than precise quantitative evidence of reciprocity.

Clearly the fact that increment-thresholds were higher when the pulse width is increased from 100 μs up to 1 ms is evidence that the visual sensation is not the same, and that there is a failure of reciprocity. The results suggest that the early recovery processes take longer for the longer pulse width exposures. It could be speculated that the elevated thresholds with the 1 ms pulses compared to 10 μs pulses is an indication that the presumed neural mechanism that compensates for the reduced bleaching potential of brief pulses (Rushton, 1964) overcompensates as the pulse width increases into the millisecond range. Although this finding is not supported by Smith's (1996) study, where for pulse widths of 6 and 11 ms at 10 Hz, he found that increment thresholds were lower than for a CW exposure, other workers have shown that for flickering light at a frequency of around 9-10 Hz, the luminosity can appear greater than the mean luminance (Bartley, 1952), in a phenomenon known as *brightness enhancement.* This enhancement is widely believed to be mediated by neural rather than photochemical mechanisms, is produced by strong stimuli, but not by weak ones, is maximal with a light-dark ratio[d] of one (Bartley, 1952), and is wavelength dependent (Wassereman, 1966).

Since the time-averaged luminance of the adapting field used by Smith (1996) was about twenty times less than that of the present study, it may be that field in the earlier study was too weak to produce the brightness enhancement effect. It could, therefore, be hypothesized that the apparent breakdown in reciprocity for the 10 Hz condition is due to the emergence of the brightness enhancement effect as the light to dark ratio increases for the longer pulse widths. Further studies would be needed to confirm this hypothesis, and to determine the precise conditions that lead to the emergence of the brightness enhancement effect for laser pulse trains.

These findings have profound implications for modeling visual functional decrements caused by military laser systems operating in the multiple pulse mode. Contrary to previous hypotheses for brief, single pulse exposures (McLin et al., 2001; Smith, 1996), reciprocity cannot be assumed, and contrast thresholds during exposure to a multiple pulse train of millisecond pulses may be higher than expected. Regardless of the cause of the increased effectiveness of the

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[d] The duration of the pulse in relation to the non-stimulation period

10 Hz, 1-10 ms pulses, this phenomenon requires closer investigation in the context of laser transient effects.

The implications for visual recovery from single pulse, flashblinding exposures are also unclear. The recovery times for the 10 Hz exposures were short (i.e. inter pulse interval: ~100 ms) and the flash energy in each pulse in this experiment was low (~4 log td-s). Whether the enhancement effect would scale up to the longer recovery times (>1 s) produced by higher energy exposures (> 6 log td-s) is unknown, since recovery processes become predominately photochemical (Barlow & Sparrock, 1964; Rushton, 1958),. The observation that the enhancement was not seen for the 3 Hz exposures, where the inter-flash recovery times were longer (~333 ms) would not support such a scaling.

To develop a more general model of these effects will require further experiments using a wide range of pulse parameters, including: pulse width (at least down to 1 μs and possibly shorter, and up to 1 s); pulse repetition frequency; energy; wavelength, and; spatial extent, so that systematic effects can be established, underlying mechanisms can be understood, and better extrapolations into the military significant, nanosecond time domain can be obtained.

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